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STELLAR KINEMATICS OF MERGING GALAXIES: CLUES TO THE ORIGINS OF ELLIPTICAL GALAXIES

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ABSTRACT

There is significant evidence suggesting that mergers of galaxies produce elliptical galaxies. To determine whether the known kinematic properties of elliptical galaxies are consistent with those of their suggested progenitors, we have examined the stellar velocity dispersion in 11 nuclear regions within starbursting infrared-luminous galaxies. All of these galaxies are in some stage of merging. The new data are presented and statistically analyzed in combination with data from the literature. We find that the kinematic and photometric properties of these galaxies suggest that they are the progenitors of low-luminosity ($L < L_*$) elliptical galaxies. Dissipative collapse of gas followed by star formation is apparently not producing a core of high-density high–velocity dispersion stars like those found in very bright elliptical galaxies. We suggest that only the ultraluminous infrared galaxies can possibly produce L_* ellipticals. We further present the results of population synthesis models that show that intermediate-age stellar populations should contribute significantly to the light of merger remnants even after the morphological signs of merging have vanished.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: interactions — galaxies: kinematics and dynamics — galaxies: photometry

1. INTRODUCTION

Both morphological evidence and theoretical models have linked merging galaxies and elliptical galaxies. Observations of advanced mergers have demonstrated that such galaxies have elliptical-like $r^{1/4}$-law light profiles (Wright et al. 1990; Stanford & Bushouse 1991). Numerical simulations of disk-disk mergers have always produced remnants that are quite reminiscent of elliptical galaxies (Toomre 1977; Barnes & Hernquist 1991; Hernquist 1992). Finally, some elliptical galaxies show subtle morphological disturbances that are likely to be the result of previous merger events (Schweizer & Seitzer 1992).

Observations of large concentrations of molecular gas in merging galaxies (Sargent & Scoville 1991; Scoville et al. 1991; Solomon, Downes, & Radford 1992) have led to suggestions that the stars formed in the gas could become the high–velocity dispersion core of a giant elliptical galaxy (Kormendy & Sanders 1992; Doyon et al. 1994). Recent work has uncovered some problems with this scenario. Models of star formation in merging galaxies suggest that while a starburst could be sufficiently intense to create an *IRAS* ultraluminous galaxy, the result of such a starburst would be a very centrally concentrated core, which is not observed in modern ellipticals (Mihos & Hernquist 1994a, 1994b). There is also some doubt as to whether the molecular gas content of cores of luminous infrared galaxies is as high as had been reported (Aalto et al. 1994; Shier et al. 1994).

If merging galaxies are to become elliptical galaxies, then they must assume not just the shape but also the kinematic properties of elliptical galaxies. Disk galaxies have different kinematics from elliptical galaxies. In particular, elliptical galaxies have higher central space densities and higher central velocity dispersions. Disk galaxies without very massive bulges cannot become elliptical galaxies through merging unless dissipative collapse occurs (Kormendy & Sanders 1992).

In this paper we discuss measurements of the stellar velocity dispersions of 11 nuclear regions of luminous infrared galaxies. We have selected for this study luminous infrared galaxies with $L_{IR} > 2.5 \times 10^{11}$ $L_\odot$ and with obvious morphological signatures of being merging galaxies or merger remnants. Only one of these galaxies, Arp 220, is an ultraluminous ($L_{IR} > 10^{12}$ $L_\odot$) galaxy. All of these galaxies are in some stage of merger, and all have very enhanced star formation. Models of disk/bulge/halo galaxies show that there is a very strong peak in the star formation rate just as the bulges of the two original galaxies merge (Mihos & Hernquist 1996), and many of the sample galaxies show morphological signs of being in this state, such as double nuclei. Comparison of the molecular gas mass and infrared luminosity demonstrate that the interstellar depletion time is quite short, especially if any low-mass stars are formed (Sanders, Scoville, & Soifer 1991). In many of the systems in the sample, the mass of young stars is a significant portion of the total nuclear mass of the galaxy (Shier 1995). Thus, if these galaxies are to form high–velocity dispersion stars in their central regions, this is the phase of the merging process in which it must occur, because this is the time when most of the merger-induced star formation occurs.

Here we present our observational results and a statistical analysis of the kinematic and photometric properties of a sample of luminous infrared galaxies. We compare the properties of the infrared galaxies to those of elliptical galaxies, in order to investigate the still uncertain evolutionary relationship between these types of galaxies. The observations discussed in this paper include both published and new observations. All of the kinematic data were obtained from the CO overtone bands near 2.3 μm, which are stellar absorption features. We have not discussed velocity mea-

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surements based on emission lines, because the dust and gas are known to have different kinematic properties in some merging galaxies (Lake & Dressler 1986; Gaffney et al. 1993). The CO bands are particularly sensitive to the younger stars, as they are stronger in supergiants than in giants (Kleinmann & Hall 1986) and much less affected by dust absorption and scattering than the optical features often used for velocity dispersion measurements. The CO bands are not completely insensitive to the effects of extinction: recent Infrared Space Observatory (ISO) results (e.g., Lutz et al. 1996) indicate that the extinction due to dust in these galaxies can be high enough to veil the most obscured nuclear regions even at 2.3 μm. However, Shier (1995) showed that the extinction at 2.3 μm has a minimal effect on the observed velocity dispersion, provided that stars near the scale radius are not completely obscured. Moreover, if the extinction is best described by a uniform screen model, as suggested by Lutz et al. (1996), then the light of all of the stars in the galaxy is uniformly absorbed, and the spectrum is unaffected by the extinction.

2. OBSERVATIONS

We observed Mrk 331, IRAS 17138−1017, and MCG +05-06-036 on the nights of 1995 September 29–30 at NASA's Infrared Telescope Facility on Mauna Kea, Hawaii. The facility near-infrared spectrometer, CSHELL (Greene et al. 1993), was used to obtain spectra of the CO (2–0) band head at 2.29 μm. Two or three overlapping subspectra were obtained for each galaxy to insure adequate coverage of the band and the continuum shortward of the band.

The spectra were reduced in a standard fashion. The sky background was removed by subtracting wobble pairs. Lamp spectra provided the wavelength calibration. Telluric absorption features were removed by dividing by spectra of hot dwarf stars. No flux calibration of the data was attempted. The slit width for these observations was 1″. Spectra were extracted from a region along the slit with a diameter equal to 1 kpc ($H_0 = 75$). Separate spectra were obtained for the north and south nuclei of IRAS 17138−1017 (Zhou, Wynn-Williams, & Sanders 1993). Our spectra are shown in Figures 1 and 2.

Velocity dispersions were determined using a χ^2 fitting technique. The CSHELL spectra have insufficient spectral coverage for the cross-correlation technique of Shier, Rieke, & Rieke (1996) to be employed. The stars 64 Dra (M0 III) and 66 Aql (K5 III) were used as templates. The CO index of late K to early M giants is very similar to that of the galaxies we observed. The recession velocity, dispersion, and line strength were fitted simultaneously. Uncertainties in the fitted parameters were determined from Monte Carlo simulations. The results of our fitting are given in Table 1.

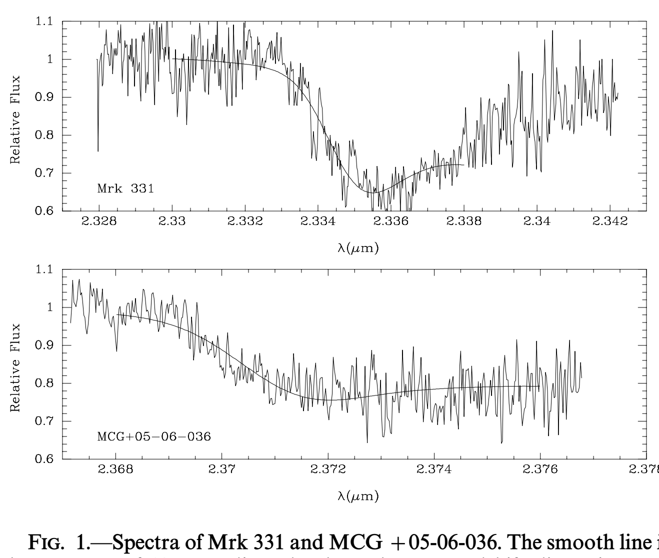

FIG. 1.—Spectra of Mrk 331 and MCG +05-06-036. The smooth line is the spectrum of 64 Dra, adjusted to have the same redshift, dispersion, and CO index as the values given in Table 1 for the galaxy.

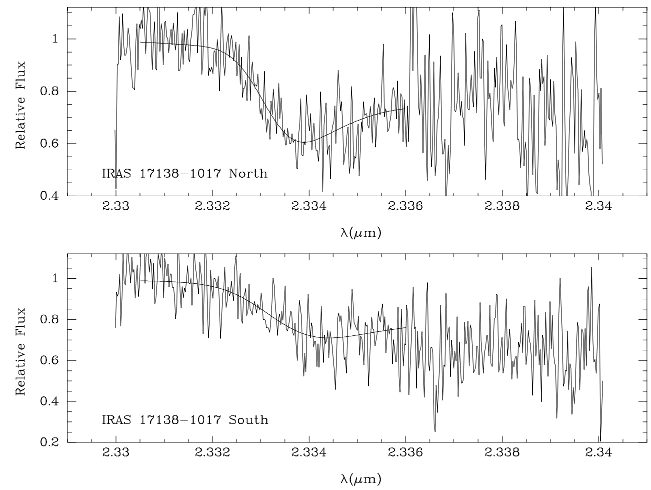

FIG. 2.—Spectra of the two nuclei of IRAS 17138−1017. The smooth line is the spectrum of 64 Dra, adjusted to have the same redshift, dispersion, and CO index as the values given in Table 1 for the galaxy.

A K_s-band image of IRAS 17138−1017 was obtained at the Steward Observatory 61″ telescope on 1996 March 31 with the HgCdTe camera (Williams et al. 1993). Flux calibration was done with BD +3°2954 from the Elias infrared standards (Elias et al. 1982).

3. DISCUSSION

We present in Table 2 a complete list of published stellar velocity dispersion measurements for luminous infrared galaxies, as obtained from the CO (2–0) absorption band head. We also present measurements of the scale radius and surface brightness. The velocity dispersions for objects not listed in Table 1 are from Shier et al. (1996), except in the case of Arp 220, for which the data are taken from Doyon et al. (1994). The scale radii and surface brightness measures are from the data discussed in Shier et al. (1996), except for the galaxies observed with CSHELL, for which new data are presented. The scale radii of the components of IRAS 17138−1017 were measured from the images obtained at the Steward Observatory 61″ telescope, and the scale radii of Mrk 331 and MCG +05-06-036 were obtained from the spatial information in the CSHELL spectra.

The galaxies in Table 2 represent a mostly random—but not complete—sample of the local infrared galaxies with

TABLE 1

RESULTS OF SPECTRAL FITTING

Galaxy	Velocity (km s^{-1})	Dispersion (km s^{-1})	CO Index (mag)
Mrk 331	5393 ± 5	101 ± 5	0.21 ± 0.02
IRAS 17138−1017 North	5197 ± 6	72 ± 5	0.22 ± 0.02
IRAS 17138−1017 South	5233 ± 11	104 ± 12	0.17 ± 0.04
MCG +05-06-036	10106 ± 4	138 ± 6	0.16 ± 0.02

TABLE 2

KINEMATIC AND PHOTOMETRIC PROPERTIES

Galaxy	r_e (pc)	Dispersion (km s^{-1})	$\langle \mu_K \rangle$ (mag $arcsec^{-2}$)	log L_{IR} ($L_\odot$)
NGC 3690 B_2	200	66	14.32	<11.3[a]
IC 694	330	135	14.20	11.5
NGC 2623	340	95	14.56	11.5
NGC 1614	460	75	14.02	11.6
IRAS 17138−1017 North	500	72	14.80	<11.6[a]
IRAS 17138−1017 South	500	104	15.08	<11.6[a]
Zw 475.056	600	151	15.51	11.4
Mrk 331	600	101	12.24	11.4
NGC 6240	620	350	13.98	11.5
Arp 220	700	150	15.18	12.1
MCG +05-06-036	1600	138	14.53	11.4

[a] These sources are in multiple nucleus galaxies with large aperture log L_{IR} equal to the indicated limit.

$L > 2.5 \times 10^{11}$ $L_\odot$. Galaxies with weak CO bands were systematically excluded from the sample: galaxies with high infrared luminosity and weak CO bands are thought to produce their high luminosity through nuclear activity and therefore have weak or nonexistent starbursts. Galaxies with redshifts above 10,000 km s^{-1} were also not observed, since the CO band falls into a region of strong telluric absorption if the redshift of the galaxy is above this limit. (Galaxies observed in Arizona were restricted to be within 8500 km s^{-1}). The result of this atmospheric redshift limit is that the sample is a luminosity-limited sample and not a flux-limited sample. A Kolmogorov-Smirnov (K-S) test shows that the redshift distribution of the sample galaxies is consistent with a luminosity-limited sample and the above redshift limits.

3.1. *Velocity Dispersion Distribution*

We find that the velocity dispersion data that we have collected are not consistent with the merging galaxies being L_* elliptical galaxies in formation. If the merging galaxies are to form high–velocity dispersion cores, then new stars with high velocity dispersion must be formed from gas that has experienced dissipative collapse. Here we assume that dissipative collapse is largely over in these galaxies based upon observations of large concentrations of molecular gas in merging galaxies (Sargent & Scoville 1991; Scoville et al. 1991; Solomon et al. 1992). The bulk of the high–velocity dispersion stars must be formed in the epoch of intense star formation, which is the current epoch for the galaxies in question. Thus, under these assumptions, the current velocity distribution is intimately tied to the eventual velocity dispersion of the galaxies.

The velocity distributions in the merging galaxies are likely to be anisotropic, and so the observed line-of-sight velocity dispersion of an object may not be a good indicator of the magnitude of the three-dimensional velocity dispersion. However, we have data on 11 galactic nuclei, and there is no reason to believe that these galaxies were all observed along a preferred axis, since the primary selection criterion was the far-infrared luminosity, which is radiated isotropically. The distribution of the observed line-of-sight velocity dispersions will provide information on the three-dimensional velocity distribution. As the galaxies evolve, the velocity dispersion will become less dependent on observer orientation.

The simplest statistical test that may be applied to the data is to observe that none of the galaxies in the sample have velocity dispersions in the range of 170–200 km s^{-1}, which is typical of L_* elliptical galaxies, nor is the mean of the velocity dispersions in this range. We find this result highly suggestive but not conclusive.

Our sample is luminosity limited, so we would expect that it would be dominated by objects with luminosities near the lower limit. The velocity dispersion of elliptical galaxies is tied to their luminosity. If the galaxies in the sample evolve in a homogeneous fashion, we would expect that the sample would therefore be dominated by galaxies of similar three-dimensional velocity dispersion, and that the scatter in the observed dispersions is largely caused by anisotropic velocity distributions.

We have used the K-S test to find the most likely velocity dispersion limit and the scatter that results from anisotropy. The K-S test requires that we construct a function describing the probability of observing galaxies with different line-of-sight velocity dispersions. This velocity dispersion function is analogous to the galaxy luminosity function. Since the velocity dispersion function has not been measured for elliptical galaxies in general, we begin with the galaxy luminosity function and convert this to a velocity dispersion function.

We assume that the luminosity function of elliptical galaxies is given by a Schechter function (Schechter 1976) with $\alpha = -1.0$ and $M_* = -21$ in the B band (Binggeli, Sandage, & Tammann 1988). Such a luminosity function has the form

$$\phi(L)dL \propto (L/L_*)^{-\alpha} e^{-L/L_*} . \tag{1}$$

We convert the luminosity function into a velocity dispersion function using the Faber-Jackson relation ($L \propto \sigma^n$) with $n = 3.2$ and $\sigma_{11} = 177$ km s^{-1} (Davies et al. 1983). The velocity dispersion function has the form

$$\phi(\sigma)d\sigma \propto (\sigma/\sigma_*)^{-5.4} e^{-(\sigma/\sigma_*)^{3.2}} , \tag{2}$$

where $\sigma_* = 182$ km s^{-1}. The selection criterion for the sample is included by requiring that $\phi(\sigma) = 0$ for all σ below some limiting value σ_{min}. The value of σ_{min} is directly related to the limiting luminosity of the sample, if we were to observe them after they had become apparently normal elliptical galaxies. We account for the probable anisotropy in the velocity dispersion in the merging galaxies by convolving equation (2) with a function of the form

$$P(\sigma_{los}) = \begin{cases} 1 , & \sigma_{true}(1 - a) \le \sigma_{los} \le \sigma_{true}(1 + a) , \\ 0 , & \text{otherwise} , \end{cases} \tag{3}$$

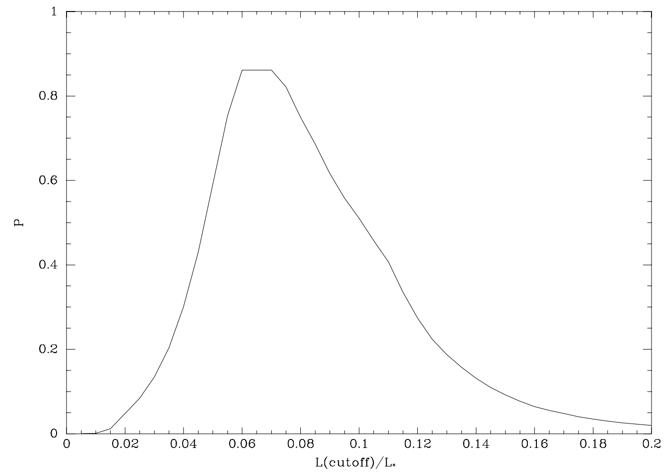

FIG. 3.—Probability of a match between the observed and theoretical velocity dispersion distributions as a function of the cutoff luminosity in the sample. The anisotropy parameter a is set to 0.65 for this set of distributions.

where a, the degree of anisotropy, is a free parameter.

We display the results of the K-S tests in Figures 3 and 4. We find that velocity dispersion functions with a cutoff of 0.03–$0.15L_*$ have a better than 10% chance of matching the observed distribution, with cutoff luminosities in the range of 0.06–$0.075L_*$ having match probabilities in excess of 85%. The most probable value for a, the anisotropy parameter, is 0.65, although any distribution with $0.5 < a < 0.75$ has a better than 10% chance of fitting the observed distribution. We conclude that most of the merging galaxies in our sample will likely become elliptical galaxies with $M_B = -17.2$ to -19.0. We suggest that very low-luminosity ellipticals might be formed by mergers of less-massive disks, which never achieve a luminosity of $2.5 \times 10^{11}\ L_\odot$. If L_* ellipticals are being created through mergers at the current epoch, galaxies like those in our sample are unlikely to be their progenitors. It is doubtful that any major mergers other than the ultraluminous infrared galaxies, those with luminosities above $10^{12}\ L_\odot$, can be the progenitors of any L_* elliptical galaxies being formed at the present time. The strong links between the ultraluminous galaxies and active galactic nuclei (Sanders et al. 1988; Hutchings & Neff 1991) would suggest that most ellipticals formed in this manner would contain a possibly dormant supermassive black hole.

3.2. *Stellar Population Models and Luminosity Evolution*

Stellar population models may be used to predict the photometric properties of the elliptical galaxies formed by these merging galaxies. We used solar-metallicity stellar population models (Bruzual & Charlot 1996) to characterize the starburst populations in the merging galaxies and to predict their properties when they have reached an age of 3 Gyr, by which time any morphological signatures of merging will have disappeared.

The methods described in a previous paper (Shier et al. 1996) allow us to measure the age and mass of the starburst populations in the merging galaxies. We used spectroscopic and photometric data from the published literature (Carico et al. 1990; Goldader et al. 1995; Veilleux et al. 1995). We find that IRAS 17138−1017 and Mrk 331 are best described as systems that have seen considerable star formation for the past 20 Myr, with starburst masses of 1.4×10^9 and $2.2 \times 10^9\ M_\odot$, respectively. The starburst in MCG +05-06-036 is probably a very short-duration burst of age 12 Myr and mass $6.6 \times 10^9\ M_\odot$.

The stellar population models suggest that the short-duration starburst will fade by about 2.2 mag in the K band in the next 3 Gyr, while the more extended burst will fade by 1.6 mag. The B-K color for a 3 Gyr–old starburst is 3.7. Since the merging galaxies currently have M_K between -23 and -24.5, we predict that the starbursts will have M_B of -17.5 to -19 at an age of 3 Gyr. Comparison of this result with the expected eventual magnitudes of the remnants in § 3.1 suggests that the starburst population continues to be an important contributor to the optical light long after morphological signs of a merger have vanished.

3.3. *The Fundamental Plane of Ellipticals*

We compare the properties of the merging galaxies to those of ellipticals by placing merging galaxies in the three-space occupied by the fundamental plane of elliptical galaxies in Figure 5, using the K-band fundamental plane for Coma (Pahre, Djorgovski, & de Carvalho 1995). We have

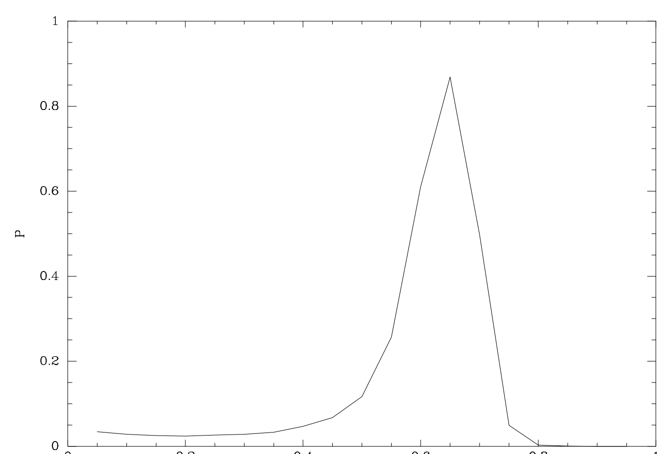

FIG. 4.—Probability of a match between the observed and theoretical velocity dispersion distributions as a function of the anisotropy parameter a. The cutoff luminosity is set to $0.07\,L_*$ for this set of distributions.

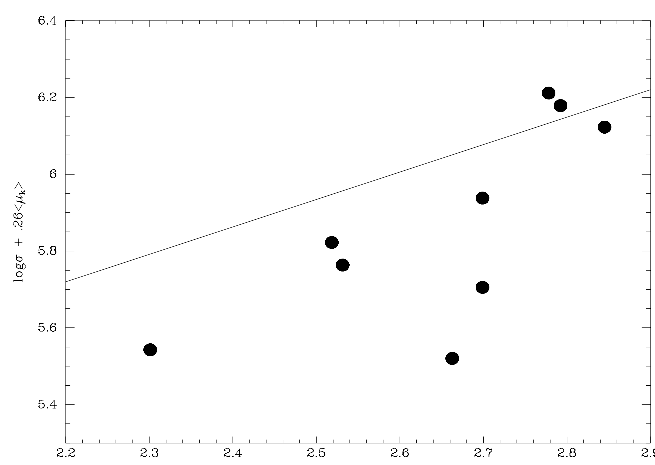

FIG. 5.—Location of the sample galaxies with respect to the fundamental plane of elliptical galaxies

converted the relation based on half-light radii to one based on scale radii using the $\eta = 3$ model of elliptical structure of Tremaine et al. (1994).

Nearly all of the observed objects fall below the plane of ellipticals, indicating that they are brighter than ellipticals with the same velocity dispersion, as would be expected from their younger stellar populations. The 1.5–2 mag of luminosity evolution expected of these objects in the next 3 Gyr would place nearly all of the galaxies approximately on the fundamental plane, assuming no evolution in the scale radius or velocity dispersion. We find that the properties of local merger remnants do not contradict the hypothesis that the merger remnants evolve into elliptical galaxies.

4. CONCLUSIONS

We have analyzed the central kinematic and photometric properties of very infrared luminous merging galaxies. We present new velocity dispersion measurements of merging galaxies based on observations of the CO (2–0) 2.3 μm band head and new K-band imagery. We combine our new data with data derived from the literature to look at the properties of a sample of 11 nuclear regions of luminous infrared galaxies. We have examined the velocity dispersion distribution of the sample, modeled the stellar populations of the sample, and compared the sample galaxies to the fundamental plane of elliptical galaxies. In analyzing these data we assumed (§ 3.1) (i) that the period of dissipative collapse of gas is largely over, that essentially all of the gas in the inner regions of the merging galaxies is being converted into stars on a timescale shorter than the dynamical timescale, and therefore that the current three-dimensional velocity dispersion is a good indicator of the three-dimensional velocity dispersion at later times; (ii) that the velocity dispersion as measured by the CO (2–0) 2.3 μm band head, with allowance for probable anisotropy, is a measure of the current three-dimensional velocity dispersion; and (iii) that the Schechter function is a good description of the galaxy luminosity function, even for galaxies of moderate luminosity, and that the Faber-Jackson relation is valid.

The major conclusions of our work are the following:

1. The kinematic and photometric properties of local mergers are consistent with their evolving into elliptical galaxies.
2. Statistical consideration of both the observed velocity dispersions and population modeling suggests that the brightest mergers within 10,000 km s^{-1} will not become L_* ellipticals. If they do evolve into elliptical galaxies, they would likely have moderate luminosities of M_B of -17 to -19 ($L \sim 0.03$–$0.15\, L_*$).
3. Intermediate-age populations may be important contributors to the light of merger remnants even after morphological signs of the merger have disappeared.
4. The L_* ellipticals, if they are formed through mergers, probably evolve from ultraluminous galaxies and may therefore contain supermassive black holes.

To further our understanding of the period of dissipative collapse in the evolution of merger galaxies, we suggest future 2–0 CO band head observations of a larger sample of galaxies. Such a sample should include both younger and more evolved mergers and a wider range of lumiosities, including a subsample of ultraluminous galaxies. These observations could be used to explore further both the assumptions and the conclusions of this work.

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